First Live Action Movie of Carbon Atoms in Action

MSD Investigator Alex Zettl, working with the world's most powerful transmission electron microscope, newly installed at the National Center for Electron Microscopy (NCEM), has produced a movie that shows carbon atoms moving around the edges of a hole in a graphene sheet. This first-ever live recording of individual carbon atoms was reported on the cover of *Science* last month.

Graphene is a single atomic layer of graphite. Due to its unique properties, it has become the subject of intense experimental and theoretical attention world-wide. For example, prior work in MSD predicted that "nanoribbons" of graphene can conduct a current in which all the electrons have the same "spin" and might therefore serve as the basis for nanosized "spintronic" devices. This prediction depends on the edges of the graphene sheet having a certain "zig-zag" configuration. But controlling or even measuring the graphene structure at this atomic-scale level is a daunting challenge.

NCEM's new state-of-the-art microscope, the Transmission Electron Aberration-corrected Microscope (TEAM 0.5), provided the solution. TEAM 0.5 is capable of producing images with half angstrom resolution, which is less than the diameter of a single hydrogen atom.

Using graphene carefully cleaved from a high-quality graphite crystal and suspended, Zettl and his colleagues used TEAM's tightly focused electron beam to introduce a hole into its pristine hexagonal carbon lattice. During the experiment, carbon atoms at the edge of the hole were being ejected from the lattice by the electron beam, increasing the size of the hole. The researchers used the same TEAM 0.5 electron beam to record for analysis a movie showing the growth of the hole and the rearrangement of the carbon atoms.

In analyzing the movies, it was observed that atoms that lose their neighbors become highly mobile, and move around rapidly, continually repositioning themselves in one configuration and then another. Understanding which of these atomic configurations is the most stable is one of the keys to predicting and controlling the stability of a device that utilizes graphene edges. While the configurations change in time, it was found that the "zigzag" configuration appeared to be the most stable. It occurred more often along the graphene edge than the other most common configuration, named the "armchair."

The discovery of strong stability in the zigzag configuration is particularly promising news for the spintronic dreams of the computer industry. Future work with TEAM may correlate the real-time atomic dynamics in graphene with such properties as electrical conduction, optical response and magnetism. This will be a major advance towards fully understanding and applying graphene to spintronic technology as well as other electronic and photovoltaic devices.

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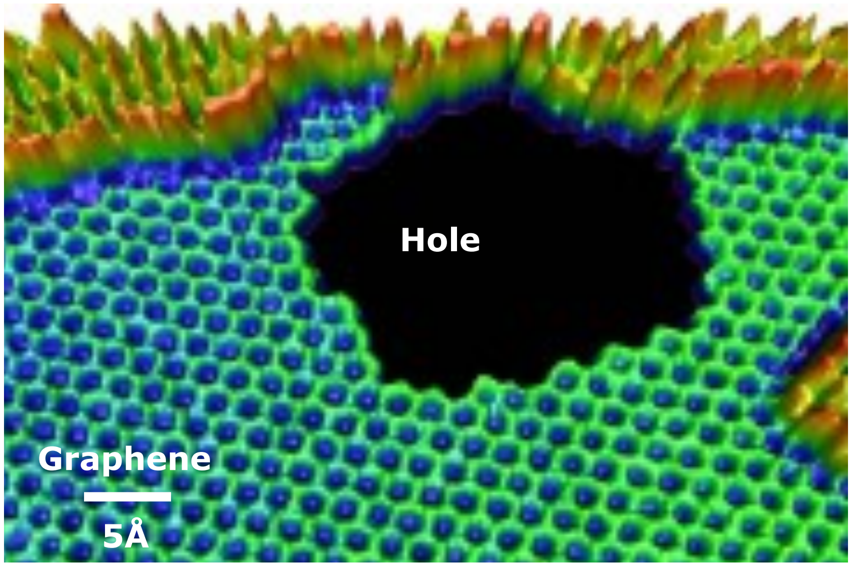
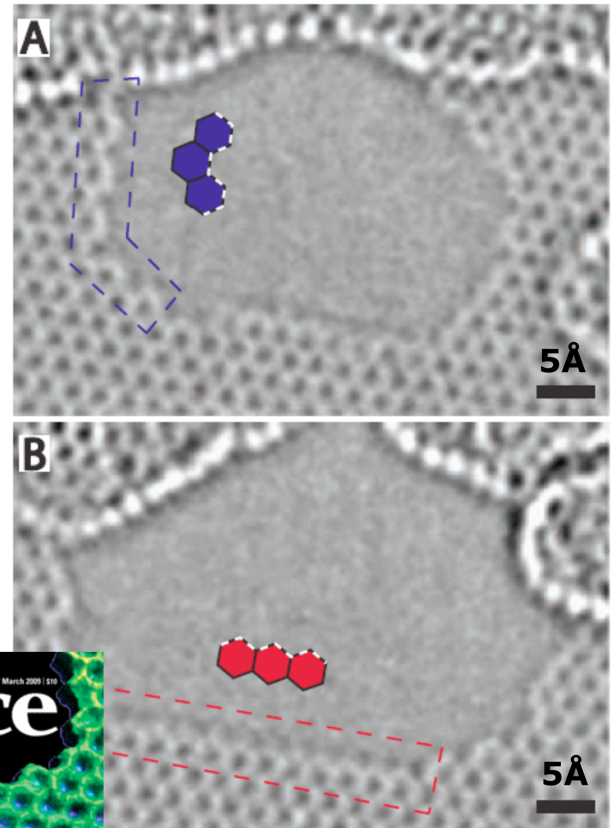
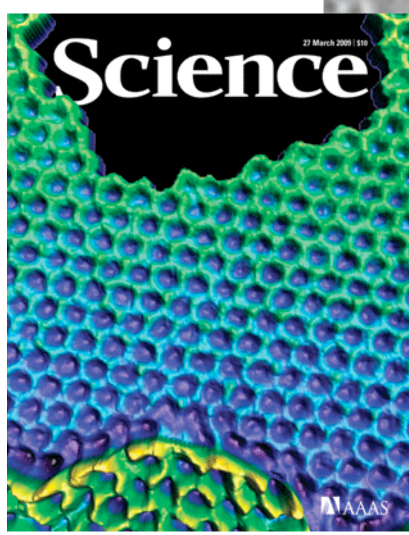


3D rendering of a hole produced in graphene by a focused beam of the TEAM 0.5 electron microscope. Graphene is one atomic layer thick, and individual carbon atoms are imaged. The hole grew in size under the exposure conditions. The same electron beam was used to capture real-time images of the carbon atoms rearranging themselves around the edge of the growing hole.



In this frame from the movie, the "armchair" configuration is observed on the left hand side of the hole. The armchair edge, outlined in blue dashed lines, is roughly 12 hexagons long and makes a 60° turn at the lower lefthand corner.

In this frame, taken when the hole has increased in size, a "zigzag edge" 12 hexagons long is observed. Overall, the zigzag (outlined in red) is the more stable configuration and shows promise for future spintronic technologies.



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